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Ceramic Filter Tests at the EPA/Exxon PFBC (Pressurized Fluidized Bed Coal Combustion) Miniplant

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16. ABSTRACT The paper describes the performance of the Acurex ceramic bag filter operating at temperatures up to 880 C and pressures up to 930 kPa on particulate-laden flue gas from a pressurized fluidized-bed coal combustion (PFBC) unit on a slipstream of gas taken after the second stage cyclone. Particle concentrations before and behind the filter, filter face velocities during the tests, and the pressure drop across the filter before the start of the cleaning cycle and immediately after the cleaning cycle were described. Three western and midwestern coals were used. Tests, ranging from 4.5 to 17 hours, in general showed that the filter could achieve high efficiency collection and was able to stabilize pressure drop with the cleaning cycle. This significant achievement in the high-temperature, high-pressure environment indicates that the ceramic fiber filter concept should receive further study to investigate longer term performance and scale-up for potential application as the final cleanup device for PFBC.

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7.2 *Fluoridkonzentrationen*

Bei der Analyse der Fluoridkonzentrationsmessungen in Meßpunkt 12 wurde dieselbe Methode wie bei den Staubkonzentrationen angewandt. Daraus ergeben sich die folgenden Werte:

$$\overline{\ln C} = 5{,}398$$
$$\sigma(\ln C) = 0{,}304$$
$$\mathrm{Exp}(\overline{\ln C}) = 221{,}0$$
$$\mathrm{Exp}(\overline{\ln C} + \sigma_s) = 253{,}2$$
$$\mathrm{Exp}(\overline{\ln C} - \sigma_s) = 192{,}8$$
$$\frac{\mathrm{Exp}(\overline{\ln C} + \sigma_s)}{\mathrm{Exp}(\overline{\ln C})} - 1 = 0{,}146$$
$$1 - \frac{\mathrm{Exp}(\overline{\ln C} - \sigma_s)}{\mathrm{Exp}(\overline{\ln C})} = 0{,}127$$

Also genügen auch bei den Fluoridmessungen fünf Messungen, um eine Abweichung von nicht mehr als 15% zwischen den Grenzwerten und dem „Mittelwert" zu erreichen.

7.3 *Lufttemperaturen*

Bei den Lufttemperaturen kann, wie bereits in Abschnitt 5 erwähnt, von einer Normalverteilung ausgegangen werden. Aus den Temperaturmessungen geht hervor, daß die Standardabweichung σ in den meisten Meßpunkten etwa 1,4 K beträgt. Wird eine Standardabweichung von 1 K bei der Temperaturmessung angenommen, dann ergibt sich für m: $\left(\frac{1{,}4}{1}\right)^2 \simeq 2$.

An einem Meßpunkt müssen die Temperaturen also zweimal gemessen werden.

7.4 *Luftgeschwindigkeiten*

Auch bei den Luftgeschwindigkeiten kann von einer Normalverteilung ausgegangen und die Gleichung (1) verwendet werden. Die Standardabweichung liegt bei den meisten Meßpunkten etwa bei 0,25 m/s. Eine Standardabweichung von 0,10 m/s erscheint als ziemlich gut, so daß sich ergibt: $m = \left(\frac{0{,}25}{0{,}10}\right)^2 \simeq 7$.

Die für jeden Meßpunkt benötigte Anzahl von Messungen ist also Sieben.

8 Danksagung

Der *Kommission der Europäischen Gemeinschaften* danken wir für die Unterstützung, welche diese Untersuchung erst ermöglicht hat.

Hoogovens IJmuiden B. V. danken wir für das Interesse und die wertvolle Hilfe bei der Untersuchung. [ST 859]

9 Schrifttum

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Ceramic filter tests at the EPA/Exxon PFBC miniplant*)

By Michael Ernst, Michael A. Shackleton and Dennis C. Drehmel, USA**)

The performance of the *Acurex* ceramic bag filter operating at temperatures up to 880 °C and pressures up to 930 kPa on particulate-laden flue gas from a pressurized fluidized bed coal combustion (PFBC) unit was shown on a slipstream of gas taken after the second stage cyclone. The particle concentrations before and behind the filter, filter face velocities during the tests the pressure drop across the filter before the start of a cleaning cycle and immediately after a cleaning cycle were described. Three western and mid-western coals were used. Test periods ranged from 4.5 to 17 hours. In general, these tests showed that the filter could achieve high efficiency collection and was able to stabilize pressure drop with the cleaning cycle. This

In der Arbeit wird über die Eignung des *Acurex*-Keramik-Schlauchfilters im schwebstoffbeladenen Gasstrom bei Temperaturen bis zu 880 °C und Drucken bis zu 930 kPa berichtet. Das Gas kam aus einem Preßluftfließbett der Kohleverbrennung (PFBC). Die Untersuchung wurde im Abgasstrom nach dem zweiten Stufenzyklon durchgeführt. Die Teilchenkonzentrationen vor und hinter dem Filter, die Filteranströmgeschwindigkeiten während des Tests, der Druckabfall am Filter vor und direkt nach einem Reinigungszyklus wurden beschrieben. Drei westliche und mittelwestliche Kohlen wurden zum Test benutzt. Die Testperioden lagen zwischen 4,5 und 17 Stunden. Im allgemeinen zeigten die Versuche, daß die Filter hohe Sammelleistungen

Ce travail est un rapport sur l'aptitude du filtre à tuyau en céramique Acurex dans le flux de gaz chargé de tissus volants à une température de 880 °C et à des pressions jusqu'à 930 kPa. Le gaz sort d'un lit de flux à air comprimé d'une combustion à charbon (PFBC). L'analyse à été (rélisée) dans le réalisée flux de gaz d'échappement après le deuxième cyclone à niveau. On décrit la concentration des particules avant et après le filtre, la vitesse de flux dans le filtre pendant le test, la chute de pression au filtre, avant et directement après un cycle de nettoyage. On a utilisé pour le test trois charbons de l'ouest et du moyen ouest. Les périodes de test se situaient entre 3, 5 et 17 heures. En général les essais ont montré que les filtres ont

Ceramic filter tests at the EPA/Exxon PFBC miniplant

was a significant achievement in the high-temperature, high-pressure environment and indicates the ceramic fiber filter concept should receive further study to investigate longer term performance and scale-up for potential application as the final clean-up device for PFBC.

erbrachten und in der Lage waren, den Druckabfall mit den Reinigungszyklen zu stabilisieren. Damit war ein wichtiges Ziel für die Hochtemperatur- und Hochdruckanlagen erreicht. Es zeigt sich, daß das Keramikfilterkonzept noch weiter untersucht werden sollte, um die Langzeiteignung der Filter und andere Möglichkeiten ihrer Anwendung als Endreinigungseinrichtung für PFBC abschätzen zu können.

rapporté de hautes capacités de ramassage, et sont à même de stabiliser la chute de pression avec les cycles de nettoyage. De cette manière on atteint un objectif important pour les installations à hautes températures et à hautes pressions. Il est montré que l'on devrait continuer à tester la conception du filtre en céramique afin de pouvoir évaluer l'aptitude à long terme du filtre et d'autres possibilités de son application comme installation de nettoyage final pour PFBC!

Schlagwörter: Entstaubung / Filtertechnik-, Prüfung / Keramik-, Anwendung / Hochtemperaturfiltration / Hochdruckfiltration

Introduction

Pressurized fluidized bed combustion (PFBC) of coal employed in a combined cycle process for steam and gas turbine power generation offers a potentially important new technique to lessen reliance upon liquid and gaseous fuels. In the gas turbine cycle energy is extracted from the hot high-pressure combustion gas by expanding it across a gas turbine. This gas which is typically at 850 °C and 1000 kPa (10 atm) pressure contains large quantities of particles consisting of fly ash and bed material. To protect the turbine components from erosion and corrosion, this particulate material must be removed before expansion across the turbine. There is a difference of opinion over what degree of efficiency must be achieved in this particulate removal (and over the significance of the role of alkali metal constituents in the gas stream) nevertheless, there is general agreement that a hot gas cleaning device is the major factor preventing commercialization of PFBC technology for power generation.

Sverdrup [1] determined analytically the tolerance of large turbines to particulate loading. *Sverdrup's* calculations indicate that cleaning of turbine expansion gas to a level of 4.6 mg/m³ (normal conditions) (0.002 gr/scf) – with all particles larger than 6 μm removed – is currently the best estimated level of cleanliness needed for turbines. This analysis predicts a maximum blade erosion of 2.5 mm (0.10 in.) in 10,000 hours of operation. Tests at *Acurex* have shown high filter efficiencies resulting in a particulate loading considerably lower than *Sverdrup's* estimate of turbine requirements.

Nearly every type of particulate removal device has been proposed for high-temperature, high-pressure (HTHP) applications, including acoustic agglomerators, molten salt scrubbers, cyclones, granular beds, electrostatic precipitators, and ceramic filters. *Weber* has published a review paper entitled "Problems of gas purification occurring in the use of new technologies for power generation" [2]. In this paper, he concludes that gravity and momentum force separators will not adequately remove particles from HTHP gas streams and will, therefore, be used only as precleaners. He also states that the required degree of cleaning can be achieved using fabric filters, and points out that fibrous ceramic materials are available which can withstand the temperatures expected in PFBC applications.

Granular bed filters have been considered the best available option for HTHP particulate control. However, tests at the *Exxon* Miniplant have shown that many problems remain to be solved before achieving high efficiency and long life in these devices [3]. These problems involve achieving high collection efficiency and cleanability at reasonable pressure drop.

Many of the particle removal devices proposed for HTHP applications operate primarily through the mechanism of inertial impaction. These devices include all forms of cyclones, scrubbers, and granular beds. Because gas viscosity increases with rising temperatures, the efficiency of all inertial devices is less at HTHP conditions than at room ambient conditions. Barrier filtration, on the other hand, is unique in that a theoretical basis exists to predict improved performance at high temperature and pressure conditions. This improvement results from using fine (3 μm) diameter ceramic fibers to construct the filter. Conventional filter media usually employ fibers 10 to 20 μm in diameter. The fine diameter fibers increase the filter efficiency enough to overcome the adverse effects of increased temperature [4].

In August 1976, *Acurex* began an *EPA*-sponsored program to demonstrate the feasibility of employing available ceramic fibers in high temperature and pressure filtration. Under this contract, the theory of barrier filtration was examined and wide spectrum of ceramic papers, cloth, and blanket felts were tested for filtration performance at room ambient conditions. A high temperature and pressure filter test rig was built. Promising media from room ambient tests were subjected to accelerated cleaning tests at HTHP conditions for 50,000 cleaning pulses. Ceramic blanket materials were shown to offer the greatest promise for further development. During 200 hour tests over a range of filter media face velocities (air-to-cloth ratio), Saffil alumina was judged to be the best commercially available material for filter application [5]. The filter media configuration employed is a loosely packed mat of fine fibers. Because the fibers are so small they achieve high collection efficiency even though the mat is not tightly held together. This porous "fluffy" mat of fibers is able to survive the mechanical stresses of cleaning because none of the fibers can exert large forces on each other because they are not firmly fixed in place. One of the test rig pressure vessels was modified to test a filter made from Saffil alumina on a slipstream at the *Exxon* PFBC Miniplant. This report presents the results of those tests.

Test description

To accomplish slipstream tests of the ceramic filter at the Miniplant, one of the existing test pressure vessels of the *Acurex* HTHP filter media test rig was modified. This modification consisted of changing the inlet location so that a dust hopper could be added to the vessel. In addition, an electronic control system was fabricated to operate the cleaning cycle. After modification, the single bag test unit could be operated

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**) Author's addresses: see author's register

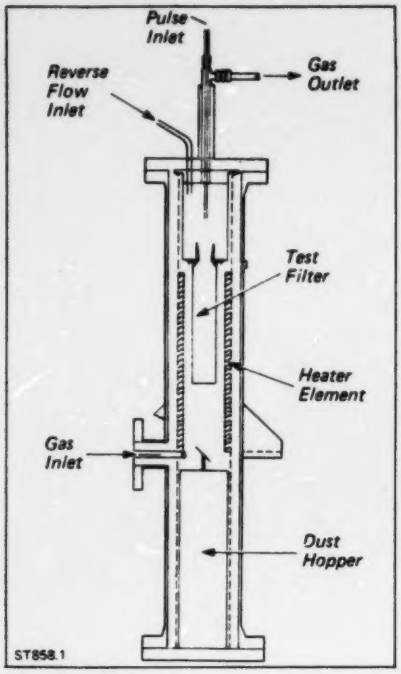

Figure 1: Filter housing pressure vessel cross section

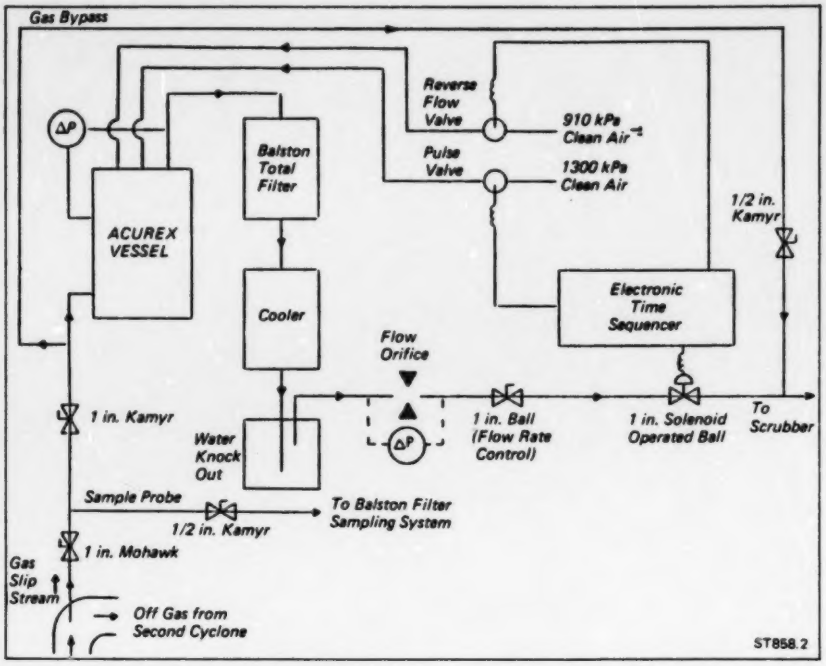

Figure 2: *Acurex* test filter installation schematic

automatically on a slipstream from the PFBC.

A cross section of the modified pressure vessel filter housing is shown in **figure 1.** Hot, dusty inlet gas enters the unit from the side below the test filter. This gas impacts against a plate on the dust hopper. Heavy particles may remain in the hopper while others travel upwards to the filter element. The filter element was 10 cm in diameter by 45.7 cm long. A heater element surrounded the test filter and was used to maintain gas temperature in the test filter zone. After removal of particles by the test filter, hot gases exit the chamber through a pipe in the top of the vessel.

Figure 2 illustrates the installation of the test filter on a gas slipstream downstream of the Miniplant second stage cyclone. The electronic time sequencer controlled the operation of the cleaning cycle. Cleaning cycle parameters were adjustable but the basic cleaning sequence was as follows:

Start on a timed interval by closing a solenoid valve downstream, taking the filter off-line.
Start a gentle reverse flow of unheated gas.
Release one or more cleaning pulses (amplitude, duration, and pulse interval are all adjustable).
Wait several seconds for dust removed during pulsing to fall into the dust hopper.
Stop reverse flow.
Open the downstream solenoid valve, returning the filter to service.

Figure 3 is a photograph of the filter unit installed at the Miniplant. The slipstream for the bag filter leaves the main flow duct through a 2.5 cm (1-inch) pipe. Two high-temperature valves, a 2.5 cm (1-inch) *Mohawk* ceramic gate valve and a 2.5 cm (1-inch) *Kamyr* ball valve, were used to isolate the filter from the PFBC. Hot gas entered the filter vessel at a point just below the bag, but above the dust hopper. Just before the filter vessel, a gas bypass line allowed extra gas to be withdrawn from the PFBC to maintain temperature in the inlet line. This bypass line was also used to preheat the inlet line prior to the start of filtration.

The filtered gas leaving the top of the filter pressure vessel cooled down to 440 °C before it entered the *Balston* total filter shown in figure 2. The weight gain of this filter was used to determine the outlet particulate concentration. The gas was further

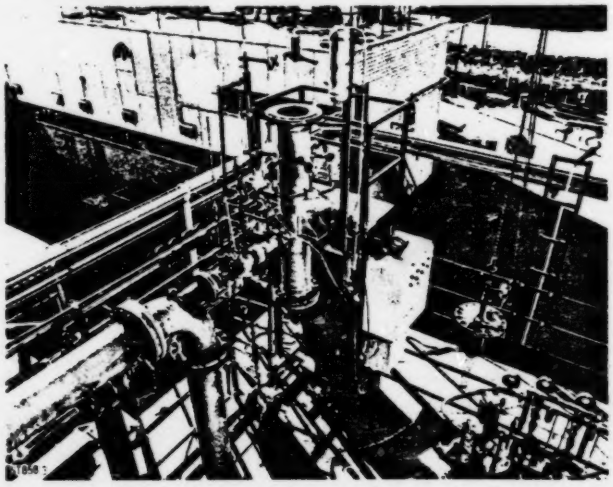

Figure 3: *Acurex* HTHP ceramic bag filter site

cooled and the water removed in a knockout vessel before it was measured through a flow orifice and expanded through a ball valve. Pressure drop across the ceramic filter was continuously measured and recorded. Inlet particulate concentration was measured by extracting a sample and passing it through a *Balston* total filter.

Various tests at the Miniplant are assigned run numbers. Tests of the ceramic filter were accomplished in parallel to other tests at the Miniplant; that is, the filter tests were not the primary reason to operate the facility. The filters were evaluated during runs 82 through 96. Runs 82 to 85 were devoted to system shakedown. Typically, a run lasted for a single working day. At the end of that time we changed test filters and began a new test the following day.

Several problems with valves occurred during the shakedown runs 82 through 85. The *Kamyr* valve failed during run 83. It was removed and not replaced. The *Mohawk* valve bonnet leaked during run 84. That gasket was replaced with a copper gasket and the valve performed satisfactorily until the alumina gate cracked during run 93. The solenoid valve that shuts off the filtered gas flow during blow back failed during run 85. The teflon seat of this valve had become damaged by hot gas. The valve was replaced with a solenoid operated ball valve which functioned well for the remainder of the test. Otherwise, shakedown ran smoothly and was mainly used to optimize the cleaning phase of the filtration cycle.

Test results

Pressure drop across the filter bags was recorded on chart paper and varied as a function of time in a manner typical for fabric filters. **Figure 4** illustrates typical pressure drop and flow recordings. Baseline pressure drop was defined as the pressure drop of a bag at the start of the filtration cycle. Graphically this point corresponds to the first point in each cycle in figure 4. Many filters were operated for several hours at baseline pressure drops close to that for a new bag. The baseline pressure drop was always between 0.1 and 5.0 kPa, usually between 0.2 and 2.0 kPa. Pressure drops before cleaning were never allowed to exceed 14 kPa to reduce the chance of bag failure. High-pressure drops generally caused the inner filter support screen to bulge into the cage onto which the filter was fastened. Baseline pressure drops were slightly higher when filtering Champion coal than when filtering Illinois No. 6 coal under similar conditions. Outlet particulate loadings were slightly lower with Champion coal than with Illinois No. 6 coal. The overall influence of coal type was small and could not be quantified from the relatively few tests completed at the Miniplant. Filter bags were used for from 4.5 to 19 hours. A summary of test conditions, pressure drops, and outlet particulate loadings is shown in **table 1.**

Filtration efficiencies for the *Acurex* ceramic bag filter were generally over 90 percent, ranging from 96 to 99.5 percent. An exact filtration efficiency was difficult to determine because of problems in measuring the filter inlet particulate concentration. Filter inlet particulate concentration was measured or calculated by three methods: (1) *Balston* total filter catch on an extracted sample, (2) mass balance around the third Miniplant cyclone, and (3) mass balance around the ceramic bag filter. The results obtained by these three techniques were not consistent as shown in **table 2.**

The test filter inlet line (**figure 5**) was 2.5 cm (1-inch) schedule 80 pipe taking a sample from a 10 cm (4-inch) schedule 5 pipe. Isokinetic flow would have been 1.15 m^3/min (41 scfm) (normal conditions). This flow was cooled from 800 °C to 450 °C before reaching the filter vessel. A bypass flow of 1.4 up to 2.3 m^3/min (50 to 80 scfm), in addition to the filtered gas, was drawn through the line to help maintain temperature near 800 °C. The flow into the filter inlet line was therefore 200 to 300 percent isokinetic. The *Balston* total filter inlet sample 6.3 mm (1/4-inch probe) was incorrectly operated isokinetically with respect to the filtered gas only, neglecting the bypass gas which was present at that point. Therefore, the *Balston* total filter samples were taken at only 30 to 50 percent isokinetic rates. For this particle size range and loading, isokinetic flow appears to be important, and this inlet loading may be treated as a lower limit of particle concentration.

The mass balance around the third Miniplant cyclone would have been a valid way to measure inlet concentration if the inlet sample of the ceramic filter had been taken under isokinetic conditions. This was not the case, and therefore this method of determining particulate concentration is not accurate.

A mass balance around the filter test vessel was attempted to resolve the inlet loading issue. Weight of the filter bags was not determined before exposure, so a tare of 0.2 kg was assumed by weighing other unexposed bags. These inlet loadings, intermediate to the other two results, can still be

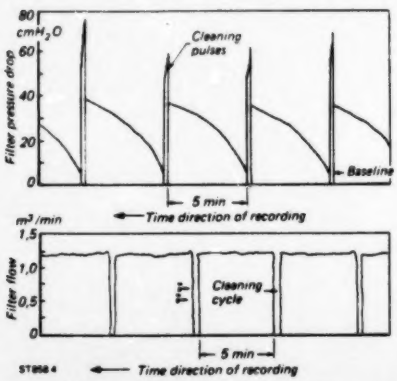

Figure 4: ***Acurex*** **HTHP ceramic bag filter pressure drop and flow**

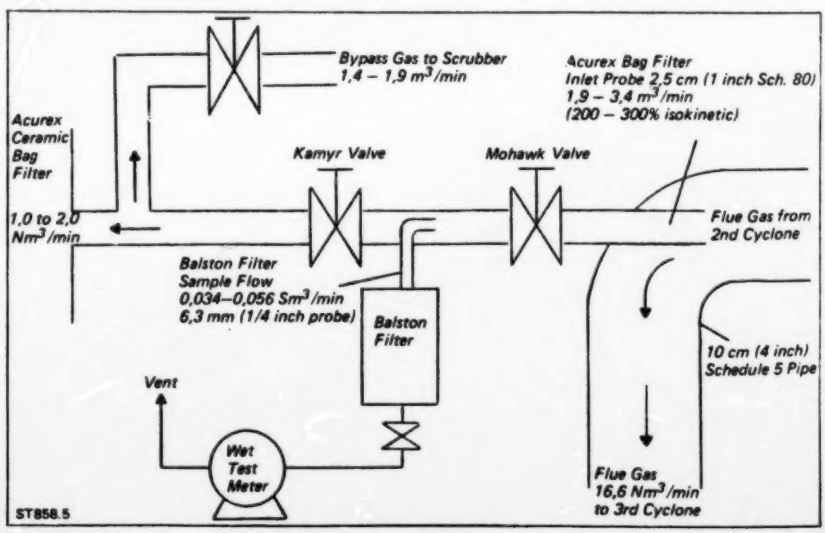

Figure 5: ***Acurex*** **high-temperature ceramic bag filter gas inlet schematic** ▶

Table 1: *Acurex* HTHP bag filtration summary

Run No.	Bag No.	Coal Type[4]	Outlet Load (g/m³)	Flow Rate m³/min	Face Velocity m/min	Average Temperature (°C)	ΔP (kPa) Baseline min	Baseline max	Max Before Cleaning	Filtration Cycle[6] Time (min)	Run Duration h
83	1	I	NA	1.42	4.0	NA	0	0.2	3.7	NA	4
84	1	I	NA	1.36	4.1	891	1.2	2.5	8.0	NA	3
85	2	I	0.0684	1.36	3.9	847	0	2.0	4.0	10	3.5
86	2[1])	I	0.0093	1.33	3.2	659	0	0.5	1.7	5	4.5
87.1	3	I	0.0146	1.70	4.0	635	0	0.2	1.0	5	3
87.2	3	I	0.0087	1.73	4.4	701	0	0.2	1.0	7	2.3
87.3	3	V	0.0027	1.81	4.5	679	0.2	0.2	1.7	15	3
88.1	3A	V	0.0205	2.01	5.4	762	0.4	0.5	2.5	20	2
88.2	3A	C	0.0137	2.27	6.0	752	0.5	3.0	6.5	20	2
88.3	3A[2])	C	0.0114	1.70	4.9	832	1.2	2.0	7.5	20	1
89.1	4	C	0.0226	1.84	5.1	801	0.1	0.1	5.0	20	1
89.2	4	C	0.0226	1.84	5.2	812	0.5	0.5	6.7	20	1
89.3	4	C	0.0226	1.42	3.9	791	0.5	2.0	7.7	20	1
89.4	4	C	0.0226	1.42	4.0	812	1.9	2.5	7.5	10	3
90	5	C	0.0089	1.42	3.9	790	0.1	2.0	7.5	5	5
91.1	5	C	0.0066	1.42	3.8	750	1.9	2.5	8.7	4	2.5
91.2	5	C	0.0034	1.42	3.8	757	2.5	3.7	9.5	4	3
91.3	5	C	0.0036	1.42	3.8	758	3.7	5.0	10.5	4	2.5
92.1	6	C	0.0059	1.13	3.1	762	0.2	0.5	5.2	10	3.3
92.2	6	C	0.0050	1.08	3.0	805	0.5	0.5	7.7	7	2.6
93.1	6	C	0.0071	0.99	3.1	787	0.2	0.5	3.5	5	3
93.2	6	C	0.0046	0.99	2.8	828	0.5	1.5	5.0	4	5
94	7[3])	C	0.0661	2.05	5.8	823	0.7	1.7	3.5	4	6
95	8	C	0.0116	1.84	5.1	797	0.5	5.0	11.2[5])	4	4.5
96.1	9	C	0.0157	1.10	2.8	693	0	0.5	6.5	10	3
96.2	9	C	0.0066	1.10	2.7	665	0.5	1.0	10.0	10	2
96.3	9	C	0.0066	1.10	2.7	665	1.0	2.5	8.7	5	1
96.4	9	C	0.0155	1.10	2.9	754	1.9	2.5	13.7[5])	5	3
96.5	9	C	0.0296	1.10	2.9	727	0	0.5	3.7	5	7
96.6	9	C	0.1870	1.10	2.6	648	0	0	0.5	5	2
96.7	9	C	0.2440	1.10	2.6	648	0	0	0.7	5	1

[1]) Bag vacuumed prior to run
[2]) Pictured in Figures
[3]) Double thickness ceramic filter material
[4]) Coal type "I" is Illinois No. 6
Coal type "V" is Valley Camp (Ohio)
Coal type "C" is Champion (Pennsylvania)
[5]) Chart recorder limit exceeded
[6]) Time for filtration between cleaning cycles

considered low because of the multitude of places where particulates could have been lost during cleaning and dismantling operations. However, from these three calculation methods a reasonable estimate can be made of the actual inlet particulate concentration.

The bag filter outlet particulate concentration was determined by passing the entire filtered gas flow through a *Balston* total filter. The total particulate concentration was obtained by weighing the total filter before and after exposure. Overall ceramic bag filter efficiencies are shown in **table 3.** These were calculated using the three methods of determining inlet concentration discussed previously. Despite some uncertainty in the inlet particulate concentrations, the collection efficiencies calculated by the three methods were generally in good agreement.

A size distribution of the outlet particulates could not be obtained. The amount of particulates on the *Balston* filter was so low that insufficient material was available for *Coulter* Counter analysis. The filters were washed off with Isoton II in an attempt to remove particulates without mechanical brushing. This method caused enough *Balston* filter material to be washed into solution to completely obscure the fly ash particulates. A clean *Balston* filter, not exposed to any fly ash but also washed with Isoton, gave a sample which had a size distribution similar to that obtained from a used filter.

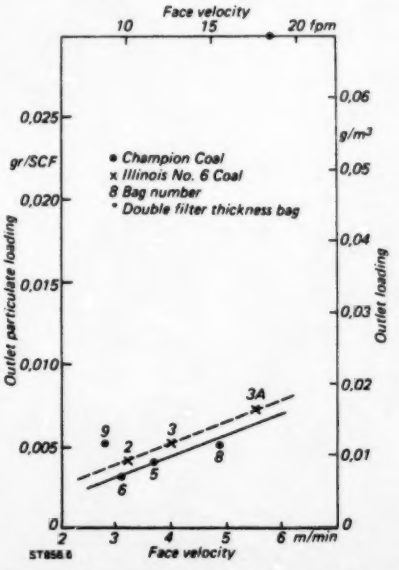

Figure 6: *Acurex* HTHP bag filter outlet loading vs. face velocity (averaged over first six hours of exposure)

During the tests at the Miniplant, eight single and one double thickness bags were exposed to PFBC conditions. Most bags were exposed for 6 hours or more. Averaging the face velocity and exit particulate concentration over the first 6 hours of new bag exposure and plotting outlet loading as a function of face velocity provided the data shown in **figure 6.** Bag No. 4 results were not recorded on figure 6 because of problems with the outlet filter. Bag No. 7 was a double thickness bag (~2 cm). Nominally filter media thickness was about 1 cm. It was physically less distorted and its pressure drop was less than bag No. 8 which was run at similar conditions, but its filtration efficiency was much lower. The reason for the discrepancy is not known (it evidently had a leak). As seen in figure 6, the particulate penetration of a bag increases with face velocity. The trend lines shown on the curve were selected by drawing a line through the Illinois No. 6 results which fell on a straight line. The data is not as precise as may be

Table 2: *Acurex* HTHP bag filter inlet particulate loadings

Run No.	Inlet Particulate Loading (g/m³) Sample by Balston Total Filter at Inlet	Calculated from Mass Balance Around 3rd Cyclone	Calculated from Mass Balance Around Filter
86	0.40	0.79	N/A
87.1	0.31	1.09	N/A
87.2	0.30	1.09	N/A
87.3	0.32	1.09	N/A
88.1	0.30	0.77	N/A
88.2	0.60	0.77	N/A
88.3	0.60	0.77	N/A
89.1	0.48	1.08	N/A
89.2	0.48	1.08	N/A
89.3	0.37	1.08	N/A
89.4	0.37	1.08	N/A
90	0.47	1.35	0.48
91.1	0.40	1.06	0.48
91.2	0.40	1.06	0.48
91.3	0.57	1.06	0.48
92.1		0.92	0.84
92.2		0.92	0.84
93.1	1.22	1.16	0.84
93.2	1.22	1.16	0.84
94	0.53	1.16	0.73
95	N/A	0.96	0.73
96.1	N/A	1.06	0.73
96.2	N/A	0.94	0.73
96.3	N/A	0.94	0.73
96.4	N/A	1.65	0.73
96.5	N/A	1.65	0.73
96.6	N/A	1.65	0.73
96.7	N/A	1.65	0.73

N/A = Not Available

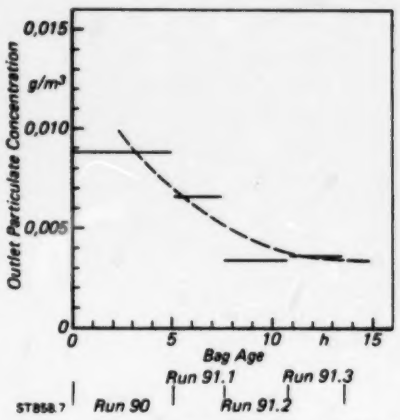

Figure 7: *Acurex* ceramic bag filter - bag No. 5 particulate penetration history

implied by this curve. One could easily make a claim for no correlation. In fact, an objective of off-line cleaning is to offset the increased penetration with velocity that is normally seen in filter tests. This data is interpreted to show little effect of coal type or of increased face velocity over the range tested.

Outlet loading plotted in figure 6 was averaged over the first 6 hours of operation. Outlet loading actually decreased as a function of time in the same fashion that a conventional filter media test would show in similar tests under ambient conditions. This decrease as a function of time is shown as **figure 7.** This bag was exposed to Champion coal fly ash at 775 °C for a total of 13 hours. Along with the decrease in filter particle outlet loading, there was an increase in baseline pressure drop from 0.1 to 3.0 kPa as expected.

Examination of the filters after a test showed that the dust cake was deposited mostly on the surface of the filter media and the dust cake could be removed easily. **Figure 8** shows bag No. 3 immediately after removal from the filtration vessel. **Figure 9** is a closeup of the same bag after a strip was vacuumed clean. This strip had the appearance of a virtually new bag indicating very little dust penetration into the media.

At the conclusion of the series of short runs, run 96, a long continuous test of the bag filter, was attempted at conditions deemed optimum for extensive testing. Filtration commenced smoothly, however, the baseline pressure drop across the bag continued to increase during the first six hours of filtration. A possible reason for this increase became clear at the conclusion of the run when it was discovered that the pressure regulator used to set the pressure of the reverse flush air was set only slightly higher

Table 3: *Acurex* HTHP bag filter collection efficiency

Run No.	Outlet Particulate Loading (g/m³)	Collection Efficiency (%) Sampled by Balston Total Filter at Inlet	Calculated from Mass Balance Around 3rd Cyclone	Calculated from Mass Balance Around Filter	Average
86	0.0093	97.6	98.8	N/A	98.2
87.1	0.00146	95.2	98.7	N/A	97.0
87.2	0.0087	97.1	99.1	N/A	98.2
87.3	0.0027	99.1	99.8	N/A	99.5
88.1	0.021	93.0	97.3	N/A	95.2
88.2	0.014	97.7	98.2	N/A	98.0
88.3	0.011	98.1	98.5	N/A	98.3
89.1	0.023	95.3	97.9	N/A	96.6
89.2	0.023	95.3	97.9	N/A	96.6
89.3	0.023	93.9	97.9	N/A	95.9
89.4	0.023	93.9	97.9	N/A	95.9
90	0.009	98.1	99.3	98.1	98.5
91.1	0.007	98.3	99.4	98.6	98.8
91.2	0.003	99.1	99.7	99.3	99.4
91.3	0.004	99.4	99.7	99.2	99.4
92.1	0.006	—	99.4	99.3	99.3
92.2	0.005	—	99.5	99.4	99.4
93.1	0.007	99.4	99.4	99.2	99.3
93.2	0.005	99.6	99.6	99.5	99.6
94	0.066	87.6	94.3	90.9	90.9
95	0.012	N/A	98.8	98.4	98.6
96.1	0.016	N/A	98.6	97.8	98.2
96.2	0.007	N/A	99.4	99.1	99.2
96.3	0.007	N/A	99.4	99.1	99.2
96.4	0.016	N/A	98.6	97.9	98.3
96.5	0.030	N/A	97.4	95.9	96.7
96.6[1])	0.187	N/A	83.5	74.4	78.5
96.7[1])	0.244	N/A	78.4	66.6	72.5

N/A = Not Available
[1]) Bag Failed

Figure 8: Ceramic filter bag (No. 3)

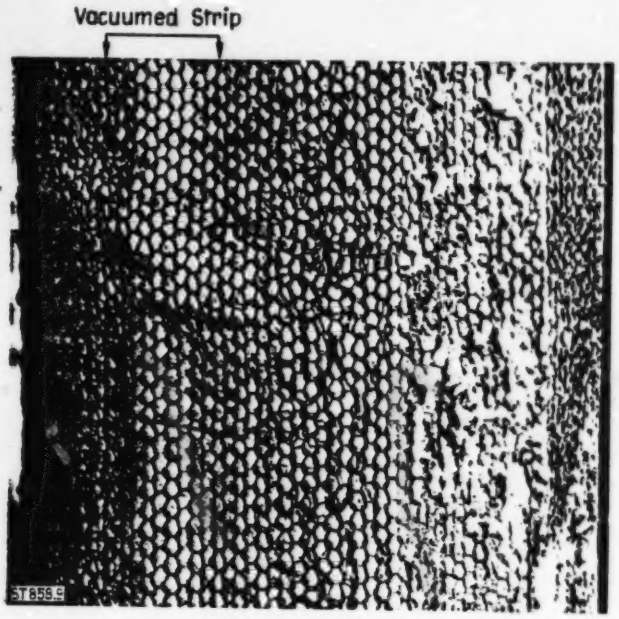

Figure 9: Ceramic filter bag (No. 3) closeup of vacuum strip

than filter vessel system pressure. It is possible that a slightly higher combustor pressure could have reduced reverse flush air flow to a level too small to clean the filter effectively. Since the reverse flush air flowrate was not measured, this hypothesis cannot be confirmed.

After six hours of filtration during run 96, a pressure drop of 12.5 kPa (50-in. H_2O) across the filter was thought to be excessive for continued bag life. The vessel pressure was reduced to 300 kPa and a full high pressure pulse blow back was initiated into the lowered system pressure. This reduced the pressure drop almost back to the clean baseline condition (0.5 kPa, 2-in. H_2O). However, outlet particulate concentration increased over the next 12 hours until it was almost identical to the inlet concentration. The run was terminated at that point. As expected, the bag had failed (see **figure 10**). The bag failure probably began with the high pulse pressure, low system pressure blow back, and was made worse by subsequent blow backs. The reason for the failure appeared to be high-temperature corrosion of the thin 304 stainless steel filter support screen. The blown out appearance was probably caused by the high pressure pulse into the lowered system pressure environment.

High-temperature corrosion of the 304 stainless steel media support screen was accelerated when the thermocouple controlling the heater elements which maintain test temperature in the filter test zone came loose from the heater element surface early in the test. This caused the heater elements, which are capable of reaching 1200 °C (2200 °F), to heat the media support screen to temperatures in excess of the 815 to 870 °C (1500 to 1600 °F) planned for. It is recognized that corrosion of a metal support screen is a potential problem in long term applications. The metal support screens used in these tests were used only for ease of construction. Flexible woven ceramic fabric screens are available to perform this function for applications requiring greater corrosion resistance.

Figure 10: Ceramic filter bag (No. 9) after run 96

Summary and conclusions

The *Acurex* high-temperature, high-pressure ceramic fiber filter system successfully completed a series of tests collecting fly ash in a slipstream of gas downstream of the secondary cyclone at the *EPA/Exxon* PFBC Miniplant.

The filter was evaluated on the Miniplant during runs 82 through 96. Runs 82 through 85 were devoted to system shakedown. Actual evaluation of the filter started with run 86 and culminated with run 96, a 19-hour continuous filtration run.

During the tests, pressure drops of under 2 kPa were maintained for over six hours average duration at face velocities of 6.4 m/min with efficiencies of 95 to 99 percent.

These tests proved the ceramic filter was cleanable while subjected to fly ash generated under PFBC conditions. High collection efficiency at high face velocity was also shown. In general, the test filter exhibited performance similar to that which would have been expected from a filter unit operating under more common conditions.

High efficiency fine particle collection results from the use of small fiber diameter (3 μm nominal) in the filter media. The ability of the media to withstand cleaning stresses results from both fine fiber diameter and low solidity. The individual fibers are not held tightly together, and because of their low mass do not exert large forces on each other. Filter cleaning is enhanced through the use of fine fibers and off-line cleaning. The high collection efficiency of the fine fibers results in collection of particles near the surface of the media. Off-line cleaning prevents reintrainment of dust from the filter element being cleaned by adjacent filters. This permits the use of high face velocities also because it is reintrainment which limits air-to-cloth ratio in currently available pulse filter systems.

The ceramic filters are not inherently expensive. High-temperature/pressure filters will cost more than standard filters, but primarily because of the pressure vessels, insulation requirements, and the use of corro-

sion resistant alloys. These factors are present in all the components of a PFBC system. Compared to the costs of these components, the filter media cost is expected to be acceptable. The ceramic materials used for the filter media and the filtration concepts are applicable to high-temperature, low pressure applications as well. This fact may create sufficient demand to lower costs still further and provide the benefits of high-temperature particle control to a wide spectrum of industry.

Recommendations

Testing of ceramic filters to date has been aimed at showing that these materials can be used for filtration purposes. This objective has been accomplished and it now seems clear that a practical high-temperature filter can be developed. Protecting gas turbines from the products of coal combustion in a PFBC is a difficult task and *Acurex* recommends that work on filtration using ceramic fiber media be resumed as quickly as possible. Component development, performance optimization, and verification of long term durability all need to be addressed for HTHP applications.

The ceramic filter may possibly be used as a "dry scrubber" by doping the dust cake with the appropriate chemicals injected into the upstream flow. The large surface area within the dust cake will enhance the scrubbing action. This may be a feasible means for removing vapor phase alkali metals or other gases from a PFBC and should be investigated experimentally.

A high-temperature filter in atmospheric pressure applications offers benefits of smaller size, less energy consumption, and lower cost. For example, heat recovery and subsequent energy savings may be enhanced with a high-temperature filter. The size of such a device could be reduced because the need for dilution air will not be as great. This capability, coupled with operation at high filter face velocity and heat recovery, could offer fine particle control at a lower total cost than is presently possible in other applications. There are also many process applications where a high-temperature filter could offer savings in energy, efficiency, or product recovery. [ST 858]

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Zur Ermittlung von Immissionskenngrößen mit Momentprobenverfahren

Von Johann-Christian Frohne und Jürgen Reis, Gelsenkirchen*)

Wenn mit Momentprobenverfahren Immissionskenngrößen ermittelt werden oder wenn auf Einhaltung von Grenzwerten geprüft werden soll, stellt sich die Frage, wieviel einzelne Momentwerte für die Ermittlung eines $^1/_2$-h-Wertes notwendig sind. Hierzu werden Antworten auf Basis vorhandener Meßreihen abgeleitet. Wenn Vorwissen aus einem Vormeßprogramm oder früheren Meßreihen über Niveau und Schwankungen der Belastung vorliegt, läßt sich für eine vorgegebene Meßaufgabe die Zahl der notwendigen Momentproben für einen $^1/_2$-h-Wert angeben und damit der Meßaufwand für Stichprobenmeßpläne zur Immissionsüberwachung reduzieren. Für homogene Kollektive, in denen bei Vormessungen 5 Momentwerte innerhalb einer $^1/_2$ h mit einem Variationskoeffizienten $\leq 40\%$ schwanken, genügen in der Regel zwei Messungen

When grap sampling is applied for determining air quality standards or monitoring, the question arises as to the number of individual instantaneous values required for the determination of a $^1/_2$-h-value. Answers to this question are developed on the basis of existing series of measurements. In case certain knowledge is available on level and fluctuations of the load, originating from a preliminary measuring programme or from previous series of measurements, the number of instantaneous samples required for a $^1/_2$-h-value can be given, so that the volume of measuring work for spot test measurement plans to monitor immissions can be reduced. For homogeneous collectives, with 5 instantaneous values of preliminary measurements fluctuating within $^1/_2$ h with a variation coefficient $\leq 40\%$, as a rule two measurements per $^1/_2$ h

Pour contrôler des caractéristiques d'immission ou l'observance de valeurs limites à l'aide de procédés d'échantillonage instantané, la question se pose de savoir de combien de valeurs instantanées individuelles on aura besoin pour déterminer une valeur $^1/_2$ h. Les réponses ci-après sont dérivées sur la base de séries existantes de mesurage. Pourvu que des connaissances résultant d'un programme ou de séries précédents de mesurage du niveau et de la fluctuation de la charge existent, le nombre des échantillons instantanés requis pour un problème défini de mesurage peut être fixé pour une valeur $^1/_2$ h, de telle manière réduisant les exigences des plans de mesurage des échantillons prises au hasard et destinés à contrôler les émissions. En cas de collectifs homogènes comportant 5 valeurs instantanées de mesurage préliminaires, fluctuant